

Elliptic flow from event-by-event hydrodynamics with fluctuating initial state

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Abstract

We develop an event-by-event ideal hydrodynamical framework where initial state density fluctuations are present and where we use a similar flow-analysis method as in the experiments to make a one-to-one v_2 comparison with the measured data. Our studies also show that the participant plane is quite a good approximation for the event plane.

Keywords: event-by-event hydrodynamics, elliptic flow, fluctuations, event plane method, participant plane

1. Introduction

Hydrodynamical calculations based on averaged initial conditions typically have problems in reproducing the experimentally observed centrality- and p_T -dependence of elliptic flow coefficient $v_2(p_T)$ at RHIC, see e.g. Fig 7.5 in Ref. [1]. Especially, in the most central collisions $v_2(p_T)$ is clearly underestimated. In this talk I will show that this problem can be solved by using ideal event-by-event hydrodynamics [2]. This model reproduces the measured $v_2(p_T)$ for all centrality classes from 0-5% to 30-40% up to $p_T \sim 2$ GeV.

2. Event-by-event hydrodynamics framework

Initial states are generated here with a Monte Carlo Glauber (MCG) model. First we distribute the nucleons into nuclei using the standard Woods-Saxon density distribution. In the transverse plane the two colliding nuclei are separated by an impact parameter b which is sampled from a distribution $dN/db \propto b$. Nucleons i and j from different nuclei collide if

$$(x_i - x_j)^2 + (y_i - y_j)^2 \leq \frac{\sigma_{NN}}{\pi}, \quad (1)$$

where σ_{NN} is the inelastic nucleon-nucleon cross section. For collisions at $\sqrt{s_{NN}} = 200$ GeV, considered here, we take $\sigma_{NN} = 42$ mb. For simplicity we do not include any nucleon finite size effects. As shown in Fig. 1 in order to define centrality classes we slice the distribution of N_{part} so that each interval contains a certain percentage of total events. Thus the impact parameter may vary freely in each centrality class.

MCG gives only the positions of wounded nucleons, but we must start our hydro with an energy density profile. We have chosen to distribute the energy density around wounded nucleons using a 2D Gaussian as a smearing function,

$$\epsilon(x, y) = \frac{K}{2\pi\sigma^2} \sum_{i=1}^{N_{\text{part}}} \exp\left(-\frac{(x - x_i)^2 + (y - y_i)^2}{2\sigma^2}\right), \quad (2)$$

where σ is a free smearing parameter controlling the width of the Gaussian. The overall normalization constant K and the initial time $\tau_0 = 0.17$ fm are taken from the EKRT pQCD+saturation model [3].

We solve the standard ideal hydrodynamic equations $\partial_\mu T^{\mu\nu} = 0$ numerically. We have neglected the small net-baryon density since we are interested only in particle production at mid-rapidity. For the same reason we can assume longitudinal boost-invariance, which reduces the numerical problem to (2+1)-dimensions. To be able to solve the hydrodynamical equations we need an Equation of State (EoS) to relate pressure and energy density. Our choice is the EoS from Ref. [4].

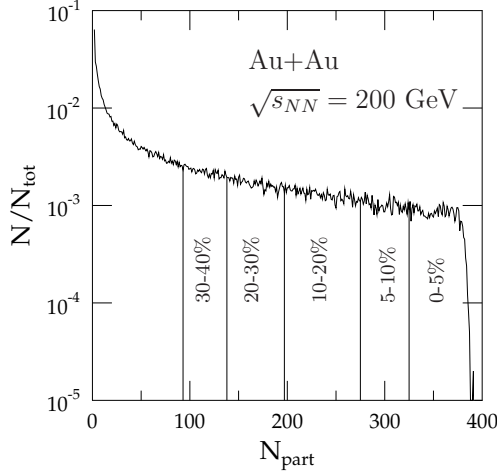


Figure 1: Our centrality class definition for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in terms of the number of participants. From [2].

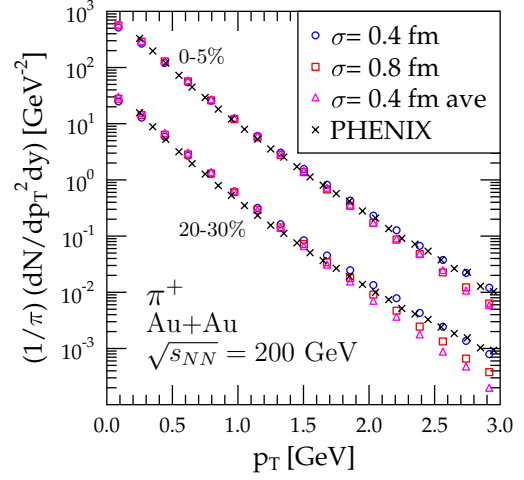


Figure 2: Positive-pion p_T spectrum for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV calculated with averaged and fluctuating initial states varying the Gaussian smearing width σ . Data are from PHENIX [7]. From [2].

We use the conventional Cooper-Frye method to calculate thermal spectra of hadrons emitted from a constant-temperature surface $T_{\text{dec}} = 160$ MeV. To get the individual final state particles for the flow analysis, we sample the thermal spectrum. We must also take into account all strong and electromagnetic decays before we can compare with the data. For this, we let the unstable thermal hadrons decay one by one using PYTHIA 6.4 [5].

Elliptic flow of hadrons is calculated here with respect to two different reference planes. The simplest way is to use the reaction plane, defined by the impact parameter and beam axis, as a reference plane. Another way to calculate v_2 is the event plane method [6], where one determines an event flow vector for each event

$$Q_2 = \sum_i (p_{Ti} \cos(2\phi_i), p_{Ti} \sin(2\phi_i)), \quad (3)$$

where we sum over every particle in the event and where ϕ_i is measured from the x axis, which is here fixed by the impact parameter. The event plane angle ψ_2 for each event is then defined to be

$$\psi_2 = \frac{\arctan(Q_{n,y}/Q_{n,x})}{2}. \quad (4)$$

Then the “observed” elliptic flow, $v_2\{\text{obs}\} = \langle \cos(2(\phi_i - \psi_2)) \rangle$, can be calculated with respect to the event plane. However, the event plane fluctuates around the “true” event plane due to a finite number of particles from which the event plane is determined. We apply the two-subevent method [6] to estimate the event plane resolution \mathcal{R}_2 , which corrects $v_2\{\text{obs}\}$ for the event plane fluctuations. The final event plane elliptic flow is obtained as

$$v_2\{\text{EP}\} = v_2\{\text{obs}\}/\mathcal{R}_2. \quad (5)$$

3. Results

We have plotted in Fig. 2 the transverse momentum spectra of positively charged pions from three hydro calculations. We can see that we get more particles at high p_T with fluctuating initial states and smaller σ , in which case larger pressure gradients are present. Most importantly, we reproduce the p_T spectra sufficiently well, so that we can meaningfully study the elliptic flow.

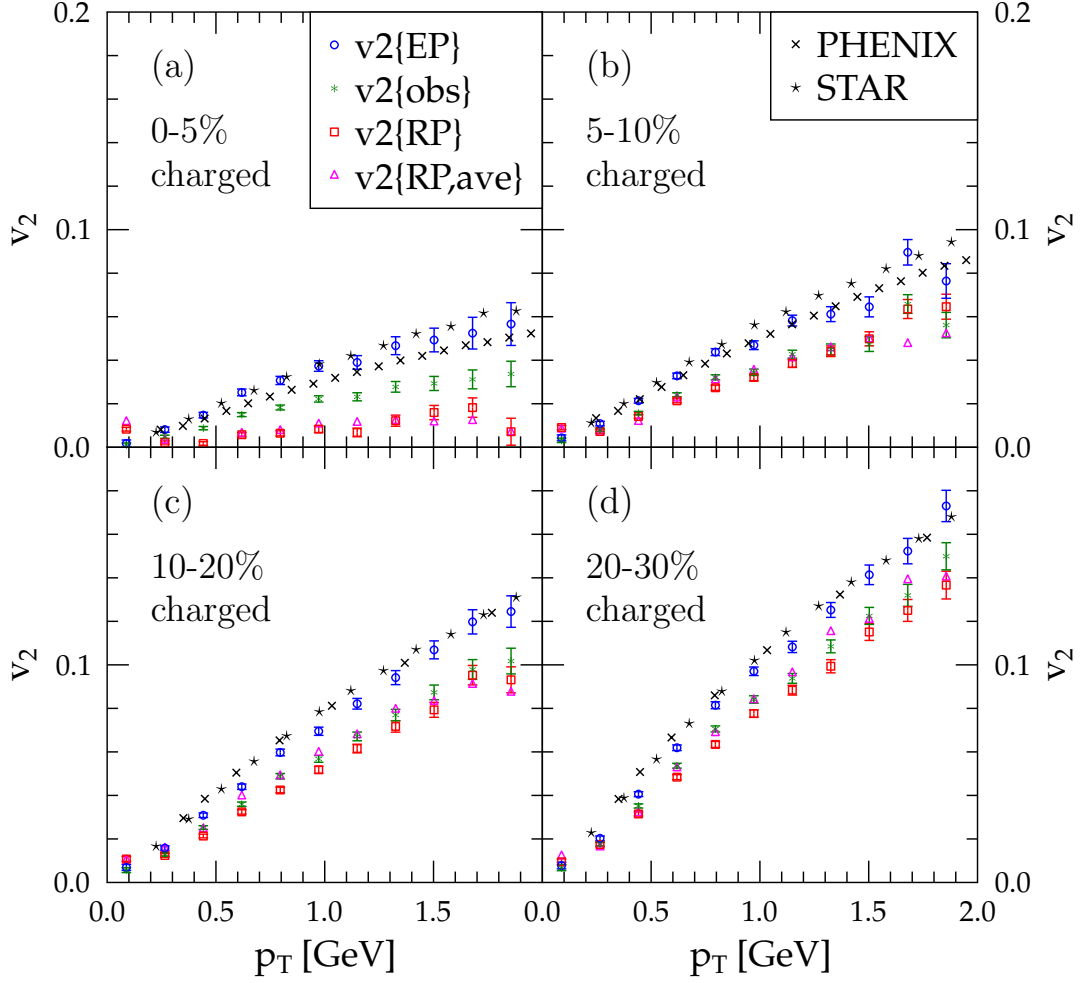


Figure 3: Elliptic flow of charged particles as a function of p_T at different centralities in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Hydrodynamical results shown are for $\sigma = 0.4$ fm. Data are from PHENIX [8, 9] and STAR [10]. The statistical errors in the experimental data are smaller than the symbol size.

In Fig. 3 we plot the elliptic flow of charged particles as a function of p_T at four different centrality classes. We compare the event-by-event calculations $v_2\{RP\}$ and $v_2\{EP\}$ and $v_2\{obs\}$ with $v_2\{RP, ave\}$ which is calculated from an averaged initial state. We remind, though, that $v_2\{obs\}$ is a non-physical quantity since it depends e.g. on the number of particles (rapidity acceptance) used in the calculation.

We see that $v_2\{RP\}$ and $v_2\{RP, ave\}$ are very similar at all centralities. This means that fluctuations alone do not generate more elliptic flow. Especially this means that the v_2 deficit persists in most central collisions even with fluctuations. However, we see that $v_2\{EP\}$ fits the measured data surprisingly well at all centralities shown here up to $p_T \sim 2$ GeV. Thus we can conclude that the reference plane definition is indeed very important in v_2 calculations and thus also in viscosity determination from the measured v_2 data.

In Fig. 4 we have plotted the elliptic flow divided by the initial eccentricity. In the data and in our $v_2\{EP\}$ points, $v_2\{EP\}$ is divided by the participant eccentricity, which is the maximal eccentricity of initial matter distribution. We have also plotted $v_2\{RP\}$ divided by the eccentricity calculated with respect to the reaction plane. We notice that both calculations are in an agreement with the data and each other.

We have also studied how well the event plane and participant plane are correlated. In Fig. 5 we have plotted the

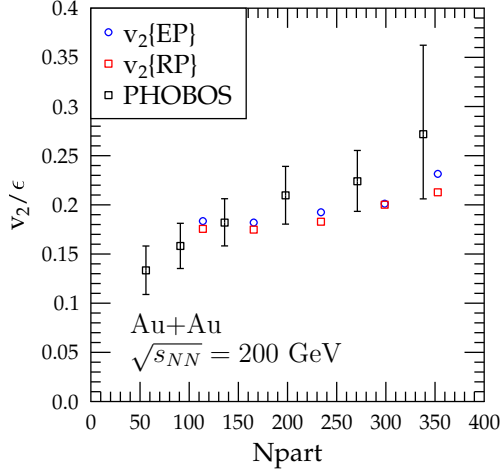


Figure 4: Integrated elliptic flow of charged particles in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV divided by initial eccentricity. The data from PHOBOS [11]. From [2].

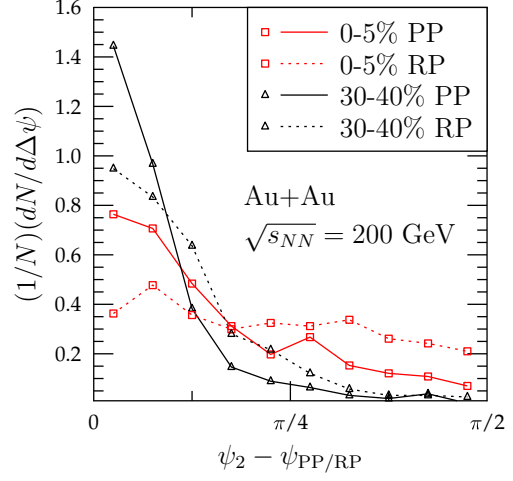


Figure 5: Correlation of the event plane with the participant plane, and with the reaction plane at two different centralities. The lines are to guide the eye. From [2].

distribution of events as a function of the angle difference from event plane to the participant plane and to the reaction plane. We see that the event plane is indeed better correlated with the participant plane than with the reaction plane. This suggest, as intuitively expected, that the participant plane is quite a good approximation for the event plane.

Acknowledgments

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